

Beyond the spectacular visualization capabilities for navigating Mars in 3-D, MarsMap provided the Pathfinder team with a valuable tool for performing mission planning and operations, science analysis, and public outreach. The Marsmap project has shown that VR can be used as a powerful method for analyzing the geology of a remote environment. Virtual reality models can be created and displayed, and analysis and measurements can be performed

with unprecedented speed and accuracy. Virtual reality may represent a giant leap forward for scientific analysis.

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## Cratering Rates on the Galilean Satellites

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In the inner solar system, impact craters are made mostly by asteroids and long-period comets. The Jupiter family of comets, whose comets are in relatively short-period, low-inclination orbits dominated dynamically by gravitational interactions with Jupiter, is relatively unimportant. These roles are reversed in the outer solar system. Asteroids rarely reach as far as Jupiter, and long-period comets are more or less uniformly distributed. The Jupiter-family comets, which swarm about Jupiter, are relatively the most important source of cratering in the vicinity of Jupiter. The purpose of this project was to determine the absolute cratering rates on the Galilean satellites, and to use those rates to estimate surface ages on Io, Europa, Ganymede, and Callisto.

Cratering rates are determined by the numbers and sizes of the comets, by their distribution in space, by their impact probabilities with the various objects, and by their impact velocities. The most important uncertainty is in the size-number distribution of the comets. This must be determined from the properties of observable comets, which are mostly comets that pass near Earth. It has recently become possible to perform extensive numerical simulations of statistically significant numbers of comet orbits as they evolve from their source region in the Kuiper belt to their many fates. These models fill in the orbital distribution of the comets, such that one can calibrate the distribution as a whole to the relatively few comets that are large enough or come near enough Earth to observe.

A single sentence summary of this work is that 20-kilometer-diameter craters, which are made by kilometer-size comets, occur on a Galilean satellite about once in a million years. The uncertainty in this rate is a factor of 5. More than 90% of the craters on the Galilean satellites are caused by the impact of Jupiter-family comets. Long-period comets contribute at the 1%–10% level, as do the Trojan asteroids (asteroids that are coorbital with Jupiter, trailing or leading Jupiter by  $\pm 60$  degrees). Main belt asteroids are currently unimportant, for each 20-kilometer crater made on Ganymede implies the disruption of a 200-kilometer-diameter parental asteroid, a destruction rate far beyond the resources of today's asteroid belt.

Study results are presented in the figure. All data are expressed in terms of the equivalent number of 10-kilometer craters. The curves are the surface ages that correspond to these crater densities at these apex angles—solid curves are ages relevant to Ganymede, the dotted curves are ages relevant to the higher cratering rate at Europa—calculated according to the assumption that the satellites have been in synchronous rotation throughout. The surface ages are those predicted using a nominal cratering rate, with the additional assumption that the Kuiper belt decays inversely with time. Ages for Callisto are not shown, but are consistent with the age of the solar system.

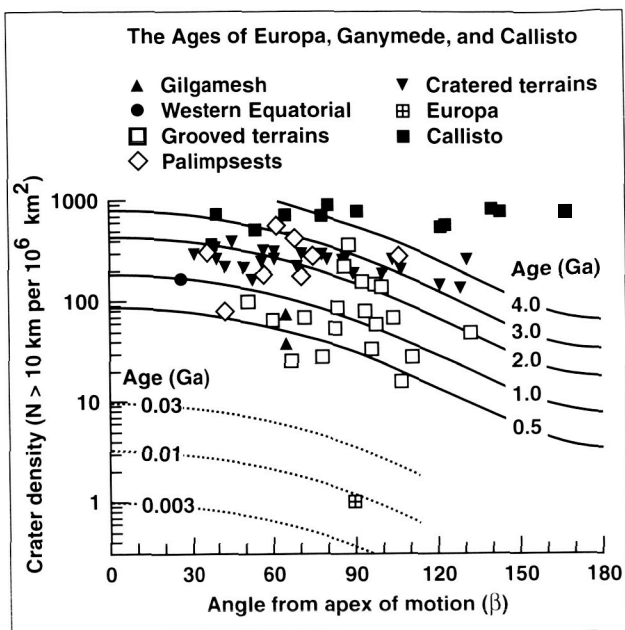


Fig. 1. Crater densities on and nominal ages of various types of surfaces on Europa, Ganymede, and Callisto as a function of the angle  $\beta$  from the apex of the motion.

The paucity of 20-kilometer craters on Europa indicates that its surface is of order 10 million years (in the figure, the datum for Europa is the nominal equivalent of five 20-kilometer craters scattered over the Moon's surface). The figure emphasizes the many ages of Ganymede. Lightly cratered surfaces (including many of the grooved terrains) are nominally 0.5–1.0 billion years old, and the cratered terrains and palimpsests (ghostly imprints of lost impact basins) are comparable to the age of the solar system. The Gilgamesh ejecta blanket in particular is assigned a nominal age of 0.7 billion years (Gilgamesh and Western Equatorial are large young-impact basins). These ages are considerably younger than the 4.56-billion-year age of the solar system and the 3.82-billion-year age of the great Imbrium impact

basin on the Moon. Such relative youth is consistent with Ganymede still being alive, in a geological sense, and is more consistent with Ganymede's currently strong magnetic field than a more conventionally ancient age would be.

On a human timescale, the Galilean satellites all rotate synchronously with their orbit; that is, they each are tidally locked to Jupiter, with the same hemisphere always facing Jupiter. They are in this sense like Earth's own Moon. A peculiarity of synchronous rotation is that there are well-defined leading and trailing hemispheres. The leading hemisphere should be more quickly cratering. The technical term for a faster cratering rate on the leading hemisphere is the apex-antapex asymmetry. It is not expected to be a subtle effect: cratering rates at the apex are more than 10 times higher than cratering rates at the antapex. The effect is illustrated by the labeled curves in the figure. But the effect is not obvious in the available data. A lack of apex-antapex asymmetry on Europa could be explained as small-number statistics, but it is not altogether unlikely that the European surface moves, either slowly on some glacial timescale, or in response to tidal heating, or catastrophically in the manner of true polar wander. Such phenomena have been predicted. Nonsynchronous rotation seems most likely if the ice is really a shell floating on a liquid ocean. It is harder to envision if the water layer is solid ice everywhere. Ganymede too shows no clear evidence of apex-antapex asymmetry. How, other than by rotation, is Ganymede to avoid a pronounced apex-antapex cratering asymmetry? And if there is no other choice, does this not suggest that Ganymede too was once, and perhaps not so long ago, home to a liquid ocean?

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